Fermi National Accelerator Laboratory

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Superconducting Dipole Magnet Requirements for the Fermilab Phase III Upgrade, SSC High Energy Booster, and Fermilab Independent Collider*

Thomas H. Nicol and James S. Kerby
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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INTRODUCTION

In July 1988 a small working group was formed to develop a conceptual design for a high field superconducting dipole magnet suitable for use in the Phase III upgrade at Fermilab. This group consisted of representatives from the Accelerator Division and the Technical Support Section. The Phase III upgrade calls for replacement of the existing Tevatron with higher field magnets to boost the energy of the fixed target program to 1.5 TeV and to add a 1.8 TeV collider program. Phases I and II consist of upgrades to the existing linac and conventional magnet systems respectively. At the time this working group was formed, development of the dipoles for Phase III was its only charge.

As the work of this group evolved it became clear that the resulting design might be applicable to more than just the proposed upgrade. In particular, it seemed plausible that the work might be applicable to the high energy booster (HEB) for the SSC.

At the Breckenridge Workshop in August 1989 interest in a third project began to surface, namely the revamping of an earlier proposal for a dedicated collider at Fermilab. In its present state it is thought to be a new machine which essentially fills the Fermilab site, representing a 3 TeV on 3 TeV collider when operated at 4.5K or a 4 TeV on 4 TeV collider when operated at 1.8K. This new proposal assumes continuation of Phases I and II, would eliminate Phase III, and would leave the existing Tevatron in place to support the fixed target program. We refer to this proposal as the FNAL Independent Collider.

The requirements for the dipole magnets for this independent collider appear to be remarkably similar to those proposed for the Phase III upgrade and the SSC HEB. The purpose of this report is to compare the conceptual design of the dipoles developed for the Phase III proposal with the requirements of those for the SSC HEB, the FNAL Independent Collider, and a hybrid design which could serve the needs of both. The Phase III design will be used as the reference point for parameter scaling.

PHASE III DIPOLE DESIGN

The development work on SSC dipoles has been watched closely by superconducting magnet designers around the world over the course of the past five years. Much of that work has found its way into the designs of other medium and high field dipoles projects; HERA at DESY in West Germany, LHC at CERN in Switzerland, and UNK at Serpukhov in the Soviet Union. The Phase III dipole project at Fermilab is no exception. It essentially consists of a $\cos(\theta)$ collared coil in cold iron, surrounded by two thermal radiation shields, supported by a reentrant post type suspension system, all inside a carbon steel vacuum vessel. The major differences between it and its SSC counterpart stem from the fact that the Phase III coil and cryostat are designed to operate at both 4.5K and 1.8K. The SSC is only intended to operate at 4.5K.

The Phase III dipole coil produces 6.6T when operated at 4.5K and 8.8T at 1.8K. In order to be compatible with the existing Tevatron refrigeration system, it contains a 2-phase channel inside the collared coil in counterflow heat exchange with the single phase flow. During operation at 1.8K the 2-phase channel is not used.

The iron is indirectly cooled by two small pipes and is truncated at the top and bottom to reduce weight and to provide room in the cryostat for piping and suspension components. It is not flooded with liquid as it is in the SSC in order to minimize the liquid volume at 1.8K. A thin stainless steel skin separates the outside diameter of the collared coil from the inside diameter of the iron yoke. Two thermal radiation shields intercept radiative and conductive heat originating at the 300K vacuum vessel. The outer shield is at 80K in both the 4.5K and 1.8K operating modes. The inner shield is at 4.5K in 1.8K mode and serves as the iron cooling return flow in the 4.5K operating mode.

The suspension system consists of two SSC-like reentrant supports and an anchor system producing very low conduction heat loads to all thermal stations.

EXTRAPOLATION TO OTHER DESIGNS

If we assume that the Phase III design is reasonably complete and that it meets its design requirements, our claim is that we can use that design as the reference point from which to quickly get a handle on the requirements of other dipole designs. Specifically, we will use the Phase III design to develop a few critical design parameters for the SSC HEB, the proposed independent collider at Fermilab, and a hybrid magnet which would satisfy the requirements of both latter projects.

The following assumptions are required in order to make these extrapolations:

a) Lorentz forces vary as the square of the magnetic field ratio

b) Lorentz forces vary directly with the ratio of coil apertures

c) Collar strength varies as the minimum thickness at the horizontal parting plane

d) Required iron width varies as the maximum magnetic field

e) Each collared coil is a two shell $\cos(\theta)$ design using 1/2 inch wide conductor

f) Collars are aluminum

Given these scaling rules the following table can be used as the starting point for designs of the other referenced projects. Bear in mind that the FNAL Phase III column contains the reference parameters.

Table 1. Summary of Dipole Parameters

Magnet Parameter		Units	FNAL Phase III	SSC HEB	FNAL Collider	HEB/Collider Hybrid
Coil aperture		cm	7.00	6.50	5.00	6.50
Conductor width		in	0.50	0.50	0.50	0.50
Collar thickness		in	1.346	0.626	0.961	1.250
Collar OD		in	7.448	5.812	5.891	7.059
Field	(1)	T	6.60	6.23	6.60	6.60
Temperature	(1)	K	4.20	4.20	4.20	4.20
Inner preload	(1)	psi	11250	9308	8036	10446
Outer preload	(1)	psi	5625	4654	4018	5223
Field	(2)	T	8.80		8.80	8.80
Temperature	(2)	K	1.80		1.80	1.80
Inner preload	(2)	psi	20000		14286	18571
Outer preload	(2)	psi	10000		7143	9286
Iron ID		in	7.578	5.942	6.021	7.189
Iron OD		in	18.11	13.40	16.55	17.72
Iron height		in	13.00	9.62	11.88	12.72
Iron x-sect		sq in	168.1	89.0	149.7	163.6
Magnet length		m	8.5	6.1	8.5	6.1
Cold mass weight		lb	19839	7663	16761	13671
Bend radius		m	1000	1000	2000	
Magnet sagitta		mm	9.03	4.65	4.52	

We do not presume that this table is the last word in the dipole design for the SSC HEB, FNAL Independent Collider, nor an HEB/Collider Hybrid design. Clearly it ignores consideration of field harmonics, refrigeration systems, structural constraints, and heat load budgets. However, we feel that it can be used to determine whether there is merit in considering a single design for more than one machine.

In order to complete the extrapolation of the Phase III dipole design to each of the other three, we need to make some assumptions about structural loading and allowable heat loads. For lack of system requirements for the SSC HEB and the FNAL Independent Collider, we assume that the shipping and handling constraints are similar to those established for the SSC main ring dipoles. Table 2 illustrates those constraints.

Table 2. Shipping and Handling Loads

Lateral load:	1.0 g
Axial load:	1.5 g
Vertical load:	2.0 g

Heat load is a little more difficult to constrain. It is safe to say that the design of the SSC main ring dipole cryostats was largely driven by very low allowable heat loads to 20K and 4.5K. Although the resulting heat loads are very low, they were achieved at the expense of some structural rigidity. For the sake of this exercise, we assume a suspension system like that used in the SSC, but with emphasis on structural stiffness as well as low heat loads.

Using the parameters in Tables 1 and 2, some knowledge of the refrigeration requirements, and estimates of the tradeoffs in the structural and thermal performance of the suspension system, cross sections can be generated for each of the referenced designs. Figures 1 through 4 illustrate the conceptual design cross sections for each referenced magnet. We have retained the iron cooling tubes in all of the referenced designs in order to minimize the total liquid volume. This indirect cooling scheme also eliminates the pressure requirements on the cold mass containment skin.

The conduction heat load to each thermal station for these four cross sections are given in Table 3. Heat loads which are largely independent of the suspension system, i.e., radiative heat transfer and residual gas conduction, are not included. All low temperature shields are assumed to operate at 20K below 8.8T and at 4.5K at 8.8T.

Table 3. Heat Load Estimates (W)

	80K	20K	4.5K	1.8K
Phase III @ 6.6T:	13.30	2.00	0.02	----
Phase III @ 8.8T:	13.08	----	2.12	0.01
SSC HEB @ 6.23T:	6.74	0.65	0.02	----
FNAL Collider @ 6.6T:	10.68	1.60	0.02	----
FNAL Collider @ 8.8T:	10.60	----	1.70	0.01
HEB/Collider @ 6.6T:	9.46	1.34	0.02	----
HEB/Collider @ 8.8T:	9.42	----	1.43	0.01

SUMMARY

None of the three magnets extrapolated from the Phase III dipole design are by any means complete as shown if Figures 2 through 4. As mentioned earlier, there are many subtleties not covered by this work. Principally, the collared coil and iron configurations must be optimized to yield the proper magnetic field parameters. In addition, concise sets of system requirements need to be generated which define the mechanical and thermal parameters particular to each design.

Our point is to take advantage of a considerable conceptual design effort on the Phase III upgrade as a means of establishing initial ideas about other projects. In spite of the lack of consideration of many operational details we feel as though the above tables and figures establish valid starting points for SSC HEB, FNAL Independent Collider, and HEB/FNAL Collider Hybrid dipole magnets.

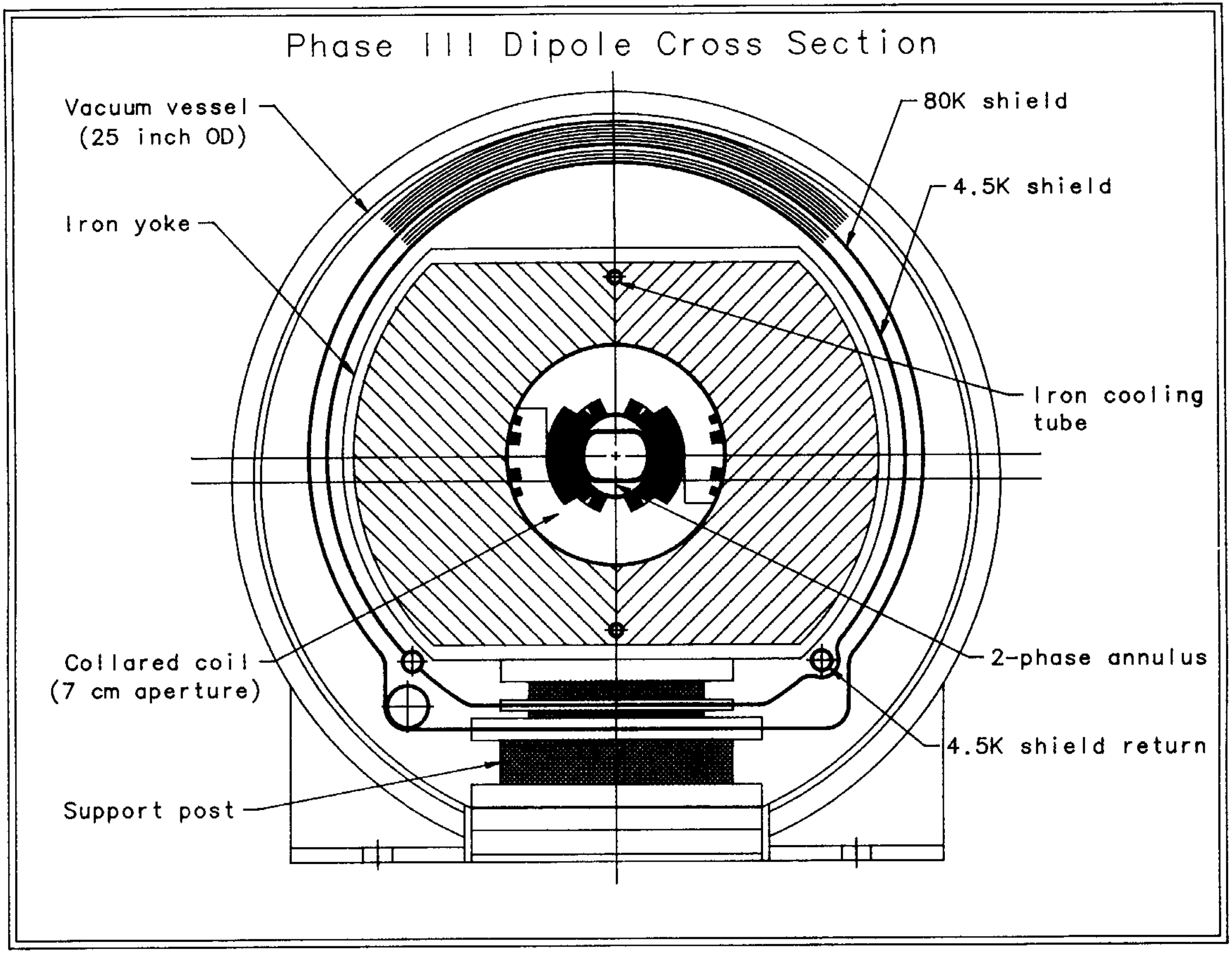
Phase III Dipole Cross Section
Vacuum vessel
(25 inch OD)
Iron yoke
80K shield
4.5K shield
Iron cooling
tube
Collared coil
(7 cm aperture)
2-phase annulus
4.5K shield return
Support post

Figure 1

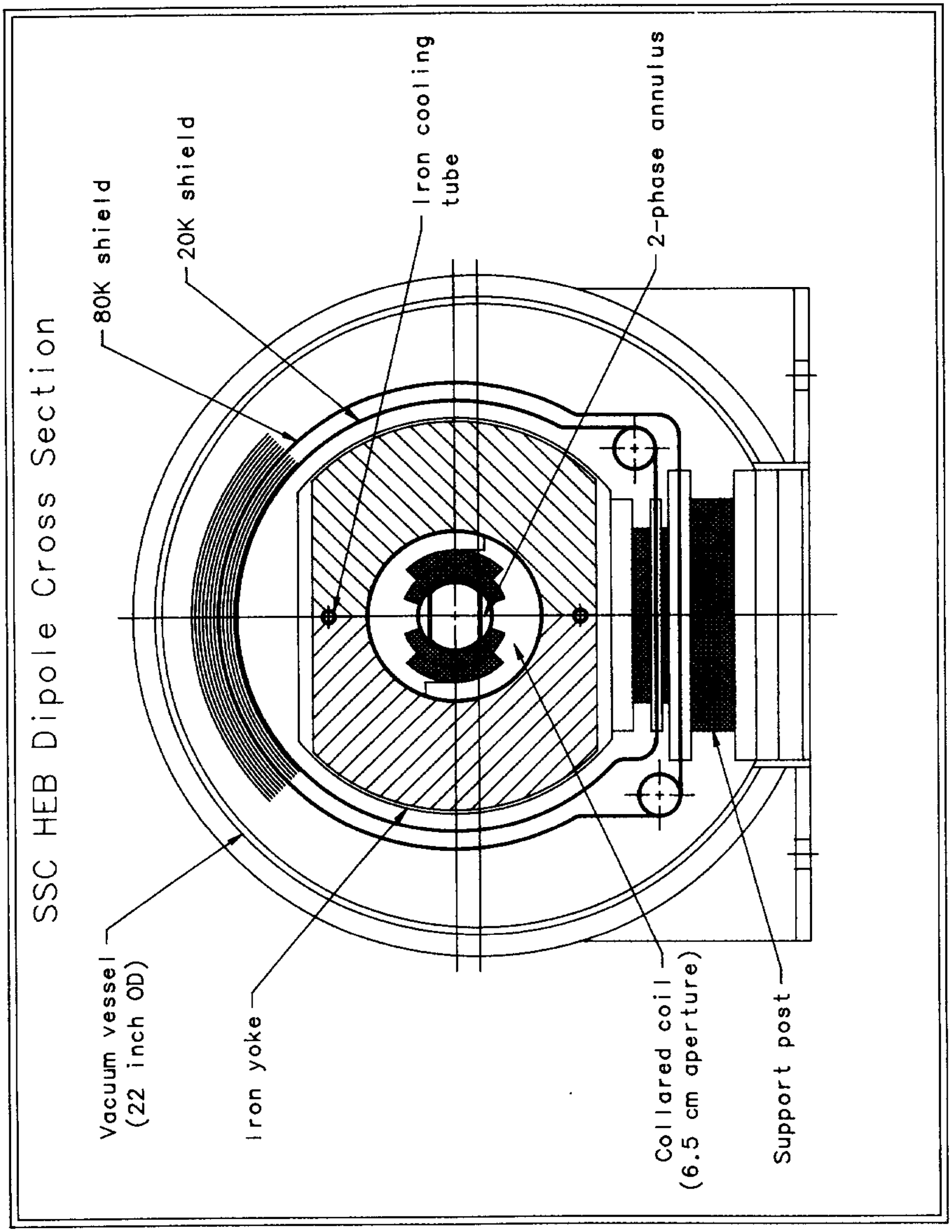
SSC HEB Dipole Cross Section
80K shield
20K shield
Iron cooling
tube
2-phase annulus
Vacuum vessel
(22 inch OD)
Iron yoke
Collared coil
(6.5 cm aperture)
Support post

Figure 2

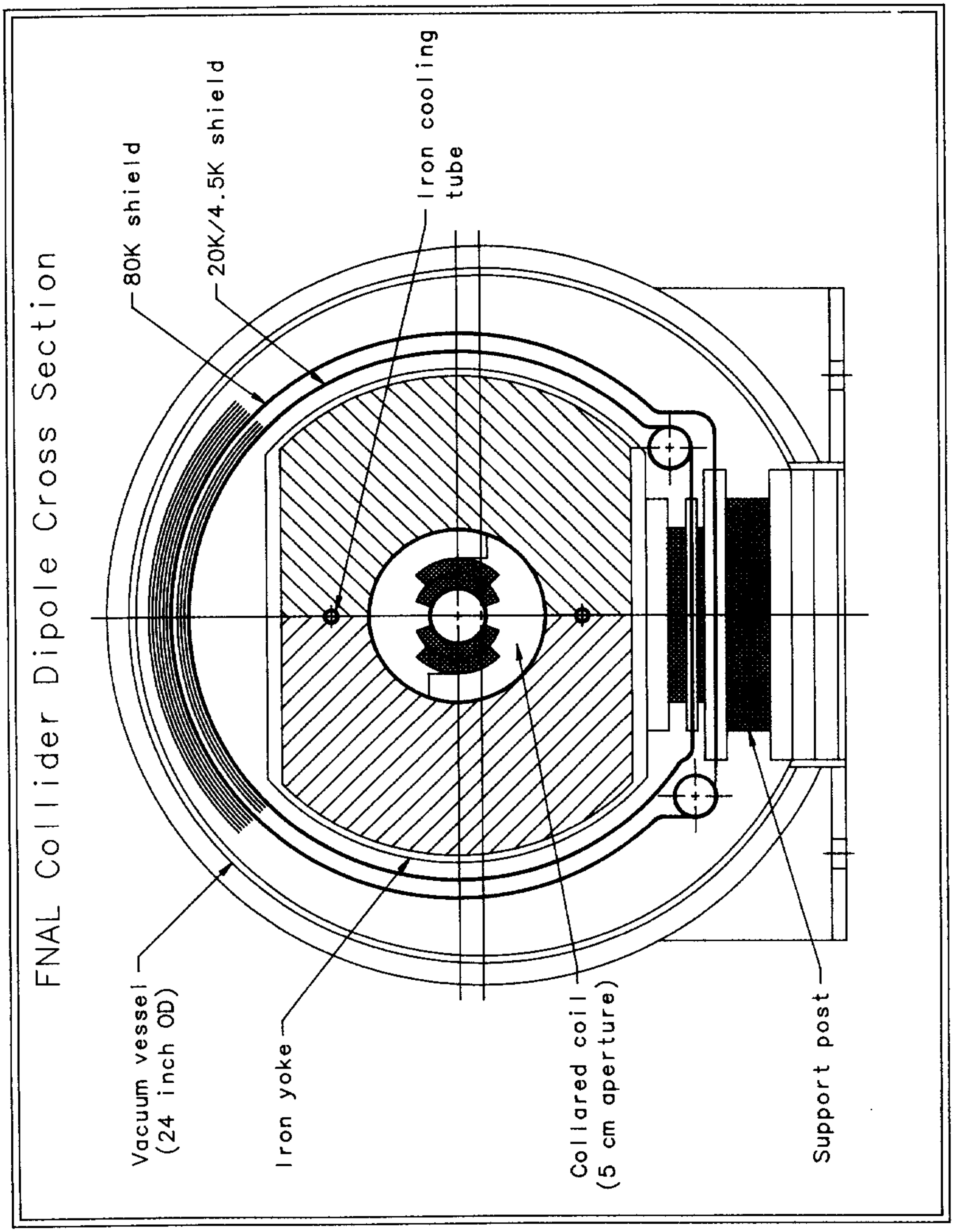
FNAL Collider Dipole Cross Section
80K shield
20K/4.5K shield
Iron cooling tube
Vacuum vessel (24 inch OD)
Iron yoke
Collared coil (5 cm aperture)
Support post

Figure 3

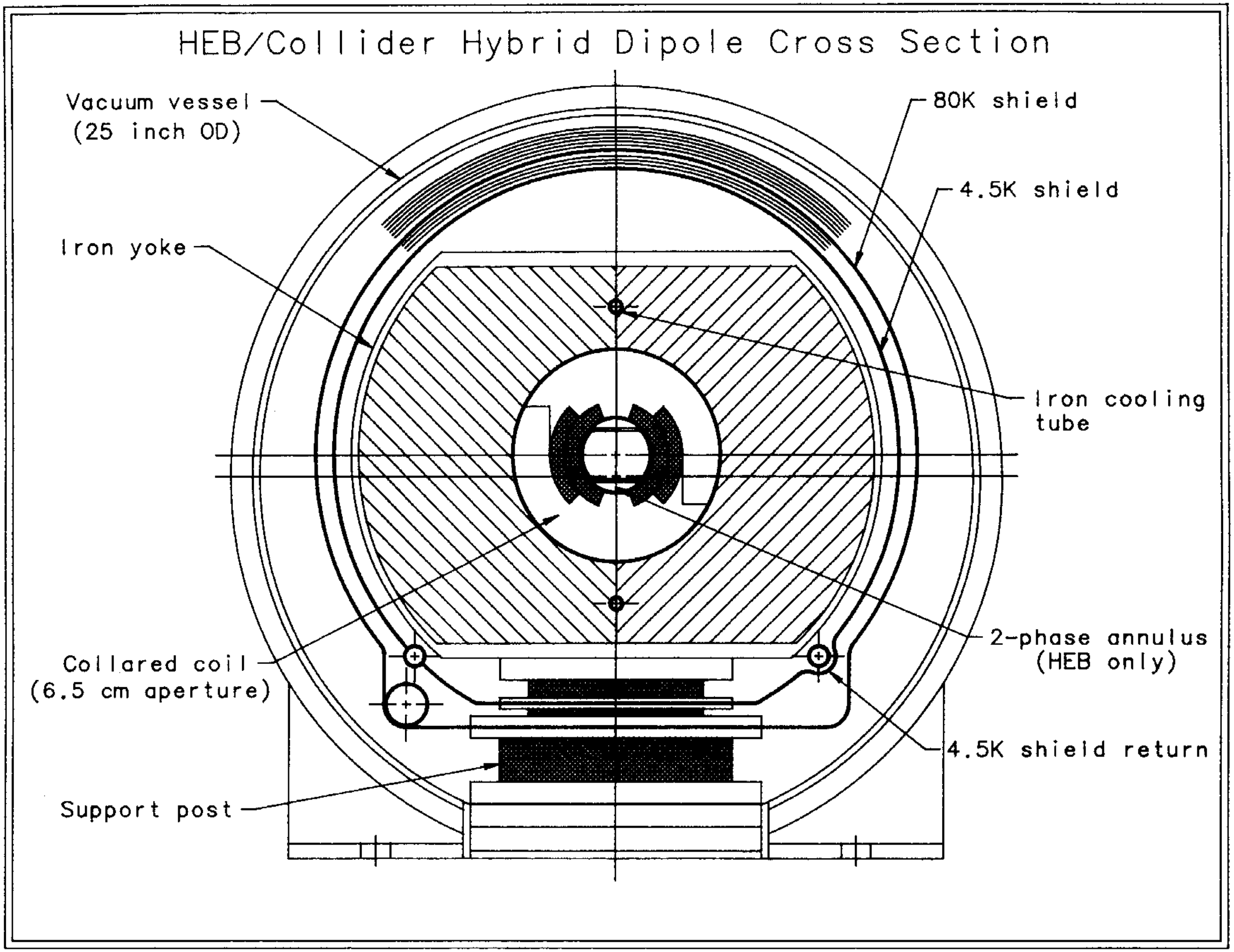
HEB/Collider Hybrid Dipole Cross Section
Vacuum vessel
(25 inch OD)
Iron yoke
Collared coil
(6.5 cm aperture)
Support post
80K shield
4.5K shield
Iron cooling
tube
2-phase annulus
(HEB only)
4.5K shield return

Figure 4